PROGRESS TOWARD A SUPERCONDUCTING OPENING SWITCH*

D. R. Humphreys
Sandia National Laboratories
Albuquerque, NM 87185

T. L. Francavilla, D. U. Gubser, and S. A. Wolf
Naval Research Laboratory
Washington, DC 20375

## Abstract

Recent developments in superconducting materials should be of interest to the pulsed power community. Niobium Nitride films have been made at the Naval Research Laboratory which can carry high currents (~10 MA/cm²) in their superconducting state, yet which have a moderately high resistivity (~100 μΩ-cm) in their normal state. Laser light of moderate energy triggers the transition in nanoseconds. The new high-temperature oxide superconductors show promise of having similar critical current densities but higher normal-state resistivities (~1000 μΩ-cm). These properties raise the possibility of making a superconducting fast opening switch. In conjunction with superconducting inductive energy storage (~100 MJ/m³), such a switch could provide the basis for very compact Terawatt pulsed power generators. Here we show some of the possible configurations, physical constraints, and scaling laws for such systems.

## Introduction

Superconducting inductors can store energy very compactly. The fundamental limit is the maximum magnetic field the material can sustain and still remain in the superconducting state. For Niobium-Tin ($Nb_3Sn$), a typical material used in large superconducting magnets, the critical field at liquid helium temperatures is about 26 T [1], corresponding to an energy density of 270 MJ/m³. Neglecting cryogenic systems and mechanical supports, this would allow an engineer to put the Marx storage energy of seven PBFA-II's (Sandia's largest pulsed power machine) into the volume of an office filing cabinet! This provides strong motivation to use superconductors in a pulsed power device.

Another motive is that superconductors could greatly simplify pulsed power generators. Figure 1 shows an idealized circuit with four superconducting components: (1) a step-down transformer $T_1$ having a single-turn high-current secondary, (2) an open switch $S_1$ which can be closed in milliseconds, (3) a storage transmission line $X_1$, and (4) a closed switch $S_2$ which can open in nanoseconds. Switch $S_1$ can simply be a segment of superconductor heated just above its critical temperature. Voltage applied to the transformer primary starts a current circulating in the storage line through switch $S_2$. The current ramps up to a desired value (kiloamperes or megamperes). The ramp-up time is typically minutes, but it can be as short as a fraction of a second [2]. Then we close switch $S_1$ and the current circulates around the storage line through the two switches. As long as the current densities and magnetic fields are sufficiently below the critical levels, the current can circulate indefinitely, perhaps for months. At the desired time we trigger switch $S_2$, which obligingly becomes a resistance and diverts current into the (matched) load. A voltage appears across the switch and load, producing a wave which travels leftward down the transmission line, inverts itself at the closed switch $S_1$, and travels back toward the load, where it terminates the voltage pulse. In a single stage such a circuit could compress the energy of a very long pulse into a few nanoseconds, offering the possibility of high efficiency and reduced complexity.

The first three superconducting components of this circuit can be made with standard cryogenic technology. The fourth component $S_2$, a superconducting fast opening switch, is at the fringe of technology. If such a switch can be developed, it would open up a wide variety of applications. A number of people have proposed using superconductors as opening switches [3-10], but as far as we know, they have not actually been used in large-scale systems, either because of lack of applications or because of limitations in the materials available. Recently, however, there have been some changes in the situation. First, a number of applications for compact Terawatt pulsed power devices are appearing. Second, some promising candidate materials among the ordinary superconductors are showing up, such as Niobium Nitride (NbN). Third, a new class of superconductors was discovered six months ago, the high-temperature oxide superconductors, on which researchers are making rapid progress. There is, therefore, a need to understand how to use the new materials in the new applications; that is, we must understand what material properties are relevant and what scaling parameters govern the systems. In this paper we show the scaling laws that apply to the circuit of Figure 1. Then we outline materials research on Niobium Nitride which the Naval Research Laboratory (NRL) has done for the past two years under a contract from Sandia National Laboratories. Lastly, we discuss the possibilities of the oxide superconductors, showing how close they are to being useful as opening switches.

## Material Properties

All the materials of interest are type II superconductors; at a relatively low applied magnetic field, flux will penetrate the conductor, but the material does not cease to be a superconductor until the field reaches much higher levels, for example ~20 T for NbN. Such high fields are necessary for compact Terawatt applications.

A related material property is the critical current density $J_c$, the maximum current density a superconductor can sustain without quenching to its normal state. It depends somewhat on the applied magnetic field and temperature, but it can be regarded as a constant for any given application. The opening switch should have as uniform a current distribution as possible, so that the current density can be brought up close to the critical level in all parts of the switch simultaneously. During the storage phase of the circuit operation, the switch current must be at least a few percent less than the critical level to prevent prefiring. For NbN, $J_c$ can be between ~0.1 MA/cm² and ~30 MA/cm², depending mainly on the fabrication process.

After bringing the current density to the desired level, the switch must be opened, i.e. it must be quenched to the normal state. One way would be to raise the current further to the critical level. However, this self-quenching method suffers from two disadvantages: (1) non-uniformities will cause some small portion of the switch to quench before the other parts, tending to produce unequal voltage

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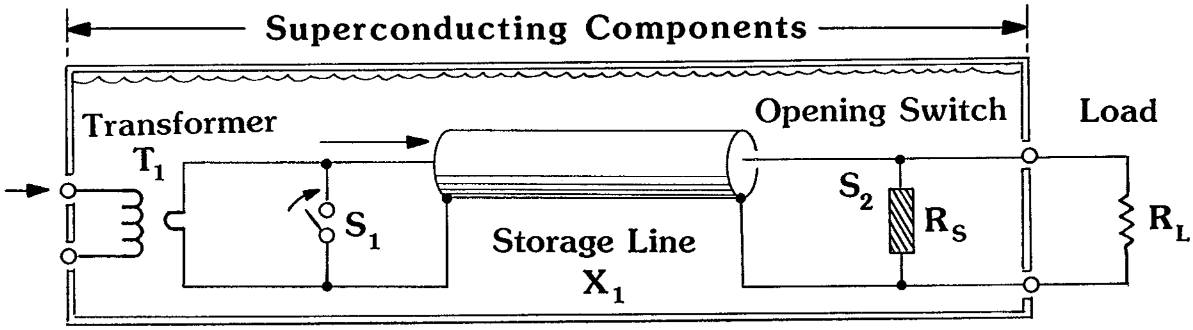


**Fig. 1.** Conceptual superconducting pulsed power generator.

distributions and arcing, and (2) the growth rates of the quenched portions are too slow for a nanosecond switch [11]. It is therefore much better to start quenching all portions of the switch simultaneously. Switching by raising the applied magnetic field to the critical level could meet that requirement, but the method has several problems: (1) it is difficult to increase magnetic fields rapidly enough for nanosecond applications, and (2) it is difficult to make the volume involved small enough to have a small trigger energy, a requirement for practical switching.

To quench a superconductor, all of the Cooper pairs [12] of electrons in the material must be broken; the electron energies must be raised from the superconducting level up to the normally-conducting state. For NbN, the minimum energy required to do this is ~0.05 J/cm³ [13]. This can be done by direct excitation of the electrons with far-infrared radiation [14], or indirectly by heating, in which case another ~0.05 J/cm³ is required to heat the lattice [13], bringing the total switching energy per unit volume, $q$, to about 0.1 J/cm³ for NbN. Inefficiencies in generating and applying the trigger energy to the switch will increase the required energy from this minimum value. The heating can be done with x-rays or particle radiation, or with optical wavelengths. At NRL an NbN film at about 50% of critical current has been switched in nanoseconds with an optical laser.

After the material has been quenched, it has a certain normal-state resistivity, $\rho$, which we want to be as high as possible in an opening switch. Niobium-titanium, a commonly-used material, has a $\rho$ of 60 μΩ-cm at liquid helium temperature (4 Kelvin); NbN ranges from that value up to 7000 μΩ-cm, depending on how it is fabricated. For comparison, high-purity copper has a resistivity of ~0.0001 μΩ-cm at 4 K and ~1 μΩ-cm at room temperature.

The NRL work has concentrated on sputtering NbN onto an insulating substrate in thin granular films. Both $J_c$ and $\rho$ for a given film depend strongly on the sputtering conditions, such as the temperature and type of substrate, the pressure and type of gas, etc. All these factors influence the grain structure of the films. For example, Figure 2 shows how one factor, the gas pressure, affects both resistivity and critical current density. (The current density can be increased tenfold by changing other factors.) Although each of these properties should be as high as possible for an opening switch, it does not seem possible to maximize both $J_c$ and $\rho$ at once. It is not immediately clear which property is more important, or how the system designer should trade one off against the other. The following section shows how to make such an evaluation. For purposes of illustration we shall refer to the following nominal values of the material properties for NbN: $J_c$ = 10 MA/cm², $\rho$ = 100 μΩ-cm, and $q$ = 0.1 J/cm³.

## Scaling Laws

In the circuit of Fig. 1, the load resistance $R_L$ and the resistance of the switch in its "open" state $R_S$ are matched to the characteristic impedance $Z_0$ of the storage line:

$$Z_0 = R_S R_L/(R_S + R_L) \tag{1}$$

In that case the circuit's efficiency $\eta$, the ratio of load power to total power dissipated, turns out to be:

$$\eta = 1 - (Z_0/R_S) \tag{2}$$

So to get a high efficiency, the switch resistance should be high relative to the storage line impedance and the load resistance. The efficiency factor affects how the current $I$ from the storage line divides into the switch current $I_S$ and the load current $I_L$ :

$$I_S = (1-\eta)I \tag{3}$$

$$I_L = \eta I \tag{4}$$

Using these equations, one can calculate the load power $P_L$ in terms of the current and resistance of the switch:

$$P_L = I_S^2 R_S \eta/(1-\eta) \tag{5}$$

The length $x$, cross-sectional area $A$, and normal-state resistivity $\rho$ of the switch determine its resistance: $R_S = \rho x/A$. Since the current density in the switch is nearly at its critical level, the current through the switch is $I_S \approx J_c A$. Using this information in equation (5), we find that the power available to the load is:

$$P_L = \rho J_c^2 \, v \, \eta/(1-\eta) \tag{6}$$

where $v = xA$ is the switch volume. Once the designer

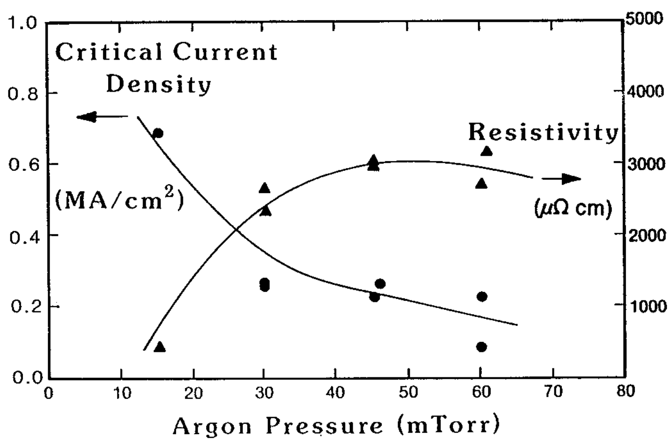


**Fig. 2.** Effect of a sputtering parameter on critical current density and normal-state resistivity.

has determined the efficiency and load power, he can calculate the volume of switch material necessary:

$$v = (P_L/p_0)[(1-\eta)/\eta] \quad (7)$$

where we have defined the critical power density $p_0$ of the material as:

$$p_0 = \rho J_c^2 \quad (8)$$

This is simply the power per unit volume the material would dissipate after self-quenching in a constant-current circuit. The larger this parameter is, the smaller the switch volume can be. For the nominal NbN defined in the previous section, $p_0$ is 10 GW/cm$^3$.

As we mentioned in the previous section, it requires a certain energy per unit volume **q** to trigger quenching in the material. Once quenched, self-heating will keep the switch in its normal state until the storage line is exhausted, after time **T**. The energy gain **G**, the ratio of load energy to triggering energy, is:

$$G = \eta(1-\eta)T/\tau \quad (9)$$

where we have defined the self-heat time $\tau$ as:

$$\tau = q/p_0 \quad (10)$$

This parameter is simply the time it would take the material to heat up by an amount equal to **q** after self-quenching in a constant-current circuit. The smaller the value of $\tau$ relative to the pulse width **T**, the higher the energy gain will be. This parameter sets a limit on how short the pulse width can be for good energy gain. For nominal NbN, the self-heat time is 0.01 ns (not including inefficiencies in triggering), thus constraining the minimum pulse width to roughly 10 ns.

The maximum pulse width is related to the energy per unit volume $u_s$ dissipated by the switch:

$$u_s = (1-\eta)p_0T \quad (11)$$

For many materials, melting begins when 5-10 kJ/cm$^3$ has been absorbed; NbN has a high melting point (about 3000 K) and does not appear to be an exception, so as long as the energy dissipated in the film itself is less than, say, 0.5 kJ/cm$^3$, it should remain well below the melting point. Using this very conservative limit and an efficiency factor of 0.9, and assuming that none of the heat has a chance to leave the film during the pulse, then for nominal NbN the maximum pulse width would be 500 ns, making the useful range of pulse widths roughly 10 to 500 ns.

After the pulse, the heat in the film will begin to boil off some of the cryogenic liquid. In liquid helium, the boiloff would be 0.4 liters per kilojoule of energy dissipated in the switch; for the maximum pulse width case above, the volume boiled would be about 190 times the volume of the switch. If the cryogen were liquid nitrogen, the boiloff would be 6 mL/kJ, about 60 times smaller. In either case, the system must be able to vent the gas and probably recycle it.

When the switch quenches to the resistive state, the current through it decreases down to the value given by eq. (3). Using the resistivity $\rho$, area, and length **x** of the switch, one can show that the electric field **E** in the material is:

$$E = (1-\eta)E_0 \quad (12)$$

where we have defined the critical electric field $E_0$ as:

$$E_0 = \rho J_c \quad (13)$$

The critical electric field is the field in the material after self-quenching in a constant-current circuit; it is the maximum field one could attain from a switch. For nominal NbN, $E_0$ is 1 kV/cm. Once the designer has decided upon a desired efficiency factor $\eta$ and a desired output voltage **V**, he can use $E_0$ to calculate the length **x** of the switch:

$$x = V/[(1-\eta)E_0] \quad (14)$$

For example, to get a voltage of 100 kV with an efficiency of 50 %, 2 meters of nominal NbN is needed, a somewhat cumbersome length for compact applications. The switch could be folded into a small volume by clever design, but the complexity of convolution is limited by the necessity for uniform current distribution, uniform triggering, and low inductance. For most applications nominal NbN appears to be of marginal usefulness; at least another order of magnitude improvement in $E_0$ is needed.

The surface flashover electric field strength of the cryogenic liquid sets an upper limit for $E_0$, beyond which further increases are not useful. Liquid helium and nitrogen have bulk dielectric strengths in the range of hundreds of kV/cm [15], similar to those of ordinary dielectric liquids. This would lead us to expect the cryogenic liquids to have a similar flashover strength, about 100 kV/cm for most liquids in the absence of particles and bubbles. (However, liquid helium has the advantage of having an unusually low dielectric constant, about 1.05, which would increase surface flashover strength [16].) From eq. (13) the electric field across the switch surface would reach 100 kV/cm for an efficiency of 90 % and an $E_0$ of 1 MV/cm. Thus the useful range for $E_0$ is roughly 1 to 1000 kV/cm; within that range, the higher $E_0$ is, the more useful the material.

The scaling parameters above were derived for the simple circuit of Fig. 1, but they seem to have a general character, providing a concise way to evaluate new superconductors in terms of the applications at hand. In summary, the scaling parameters are:

| Parameter | Symbol | Nom. Value |
|---|---|---|
| Critical power density | $p_0 = \rho J_c^2$ | 10 GW/cm$^3$ |
| Self-heat time | $\tau = q/p_0$ | 0.01 ns |
| Critical electric field | $E_0 = \rho J_c$ | 1 kV/cm |

## Niobium Nitride Experiments

The main purpose of the research done at NRL on NbN has been to find out how to optimize the properties of the films by controlling various sputtering deposition parameters, mainly the substrate temperature, amount and type of reactive gas, and gas pressure. All of these factors had important effects, some of which were described in a previous publication [17]. One of the most important efforts was to raise the critical current density in large samples. Microscopic samples of NbN had been shown to have very high values of $J_c$, about 30 MA/cm$^2$ [19], but fo8 some time we were unable to approach those results in larger samples using planar films on a sapphire substrate. Then we tried cylindrical films on a quartz substrate and found a considerable improvement, probably because of the absence of edge effects, producing greater uniformity of current density. (The microscopic samples did not have edge-effect problems because the scale of the edges was smaller than the

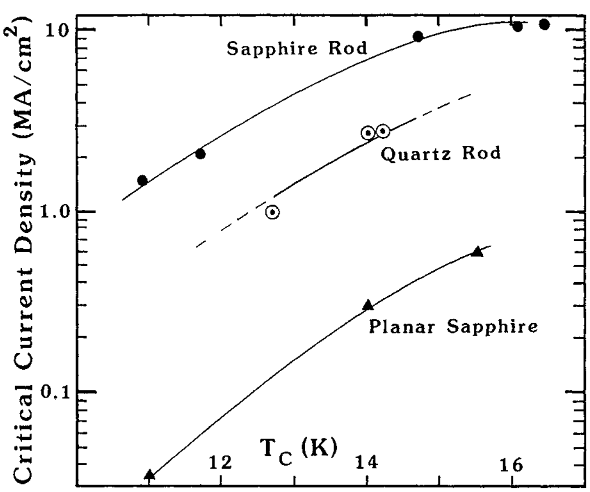


**Fig. 3.** Critical current densities and temperatures for NbN films on various types of substrate.

coherence length, an important scale size in type II superconductors.) A further improvement occurred by changing the cylindrical substrate from quartz to sapphire. Sapphire transfers heat much faster than quartz, and thus thermally stabilizes the film against local fluctuations in current density and temperature. Figure 3 shows the critical current densities of a number of samples, plotted against their critical temperatures, with the three types of substrate as a variable. Note that the change from planar to cylindrical sapphire substrates resulted in more than a tenfold improvement in $J_c$. The highest $J_c$ attained in these samples was 10.5 MA/cm², to our knowledge the highest value obtained in a macroscopic sample of NbN. However, the resistivity of the same sample was rather low, 42.5 μΩ-cm, and so the critical power density was 4.7 GW/cm³, lower than the nominal value. The highest resistivity attained in earlier runs was ~7000 μΩ-cm, but the corresponding value of $J_c$ was low. At this point, the "nominal" values are a little better than our best samples, but they seem to be fairly representative of what can be attained.

## Oxide Superconductors

The recently-discovered "high-temperature", "ceramic," or "oxide" superconductors could make superconducting pulsed power devices much easier to build. The material $YBa_2Cu_3O_{7-\delta}$ in particular has a critical temperature greater than 90 K, well above the temperature of liquid nitrogen, 77 K. Liquid nitrogen systems are much simpler than liquid helium systems, mainly because the heat transfer rate is much lower. Liquid $N_2$ is also much less expensive and more available than liquid He. For opening switch applications, liquid $N_2$ is advantageous because its latent heat is much greater, resulting in 60 times less boiloff (as we mentioned above).

Most of the normal-state resistivities reported for the new materials are above 1000 μΩ-cm. Critical current densities as reported have been increasing rapidly, from initial values of 1 KA/cm² up to several recent mentions of ~1 MA/cm² at 77 K [19,20]. If either $J_c$ or $\rho$ increases much more, the new materials would have a better critical electric field $\mathbf{E_0}$ than Niobium Nitride, and they would be very attractive for opening switch applications. However, the switching energy density **q** deserves careful attention. The lattice heat capacity is much higher at 77 K than it is at 4 K, so triggering by simple heating would be inefficient. On the other hand, we estimate that direct excitation of the electron pairs by mid-infrared radiation would only require about 0.15 J/cm³. Experiments should be performed to determine the practicality of this approach.

## Conclusions

Superconductors could become "superswitches." Circuits and applications of interest exist, niobium nitride is on the threshold of being useful, and the new oxide superconductors have great potential. These possibilities make the present race in superconductor development a fascinating spectator sport for pulsed power designers, with the scaling parameters listed in this paper being a good way to keep score. If the scores get high enough, the leading contenders can be harnessed to pulsed power applications.

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